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USING SPACECRAFT TRACE CONTAMINANT CONTROL SYSTEMS TO CURE SICK BUILDING SYNDROME

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ABSTRACT

Many residential and commercial buildings with centralized, recirculating, heating ventilation and air conditioning systems suffer from "Sick Building Syndrome." Ventilation rates are reduced to save energy costs, synthetic building materials off-gas contaminants, and unsafe levels of volatile organic compounds (VOCs) accumulate. These unsafe levels of contaminants can cause irritation of eyes and throat, fatigue and dizziness to building occupants. Increased ventilation, the primary method of treating Sick Building Syndrome is expensive (due to increased energy costs) and recently, the effectiveness of increased ventilation has been questioned. On spacecraft venting is not allowed, so the primary methods of air quality control are; source control, active filtering, and destruction of VOCs. Four non-venting contaminant removal technologies; strict material selection to provide source control, ambient temperature catalytic oxidation, photocatalytic oxidation, and uptake by higher plants, may have potential application for indoor air quality control.

INTRODUCTION

The similarities between providing spacecraft trace contaminant control and treating the indoor air pollution problems in "tight" buildings have been recognized for several years (Limero et. al. 1990). Both spacecraft and "tight" buildings support continuous human occupancy for extended periods of time; both recirculate air through a closed volume with limited venting, both have contaminants introduced through off-gassing of materials and human metabolic activity, both must remove a wide range contaminants found at very low concentrations, and both must use removal techniques that are simple, regenerable, robust, operate at ambient temperatures and pressures, and have low energy requirements.

The increased cost of energy has forced the designers of commercial and residential buildings to seal windows, further limit the exchange of outside air, and recirculate indoor air longer before venting. Commercial and residential buildings are becoming more and more like spacecraft (Litten, 1993). Because the needs of air quality control are similar for spacecraft and commercial and residential buildings, air quality control techniques considered for spacecraft may have potential application in commercial buildings.

Indoor Air Quality is a complex field involving ventilation, temperature control, atmospheric monitoring, smoke and thermodegradation events, microbial and viral control, and particulate removal. This paper will focus on the control and removal of Volatile Organic Contaminants (VOCs) from spacecraft and "tight" residential and commercial buildings.

SICK BUILDING SYNDROME

An epidemic of illness confined to a group of people residing or working in a building with no secondary spread of illness to persons encountered outside of the building has been ascribed to Sick Building Syndrome (SBS). Symptoms of building occupants often include irritation of eyes and throat, headache, dizziness, and fatigue. The National Institute for Occupational Safety and Health (NIOSH) has noted a marked increase in the number of complaints related to office buildings since 1970 (Walsh, 1984). 71% of the buildings investigated by the NIOSH were hermetically sealed and had central air conditioning which recirculated a portion of filtered air. The increase in incidence of Sick Building Syndrome has been largely attributed to two factors; the use of new synthetic building materials that continuously off-gas volatile contaminants, and the use of recirculating centralized Heating Ventilation and Air Conditioning (HVAC) systems operating at reduced ventilation rates in order to decrease energy costs (Brooks, 1992).

Building materials, especially carpet, caulking, adhesives, paint, and particle boards have been found to emit VOCs. Table 1 summarizes emissions from some materials tested in chamber studies. New buildings have been found to have the highest concentration of VOCs (Baechler, 1991). Two new buildings were found to have levels of total organics up to 400 times greater than outside air. After six months, concentrations dropped to 30 times outdoor levels. Molhave (1985) suggests that SBS may result from the additive or synergistic effect of the complex mixture found in buildings, rather than any single component. Molhave's work suggests that a major component of SBS may be common indoor organic vapors at levels far below occupational health standards.

	Emission Rate μg/m²/h			
Sample	Aliphatic Hydrocarbons	Aromatic Hydrocarbons	Halogenated Hydrocarbons	Total Organics
Cove Adhesive	sat*	sat*	sat*	>5000
Latex caulk	252	380	5.2	637
Latex paint A	111	52	86	249
Carpet adhesive	136	98	nd	234
Rubber molding	24	78	0.88	103
Telephone cable	33	26	1.4	60
Vinyl cove molding	31	14	0.62	46
Linoleum tile	6	35	4	45
Carpet	27	9.4	nd	36
Particle board	27	1.1	0.14	28

* detectors were saturated during this analysis. Total organic value is a minimum number. It is estimated that cove adhesive is one of the highest emitters of VOCs.

Table 1. Summary of Emission Rates from Building Materials (from Baechler, 1991)

Recommended ventilation rates have decreased in an effort to make buildings more energy efficient. In 1975, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) dropped their recommended rates from 10 cubic feet per minute (cfm) per occupant to 5 cfm/occupant. Since 1981, this minimum is considered appropriate only where smoking is not permitted; 20 cfm/occupant is recommended where smoking is permitted (Turiel, 1982).

Remediation of a building with indoor air quality problems almost always involves increased ventilation. This technique can be effective (Sterling 1981) but expensive, with increased energy costs and the cost of modifying an existing ventilation system. The Du Page County IL courthouse was closed for six months and redesign and retrofitting cost $2.8 million (Sjostrom, 1993). New buildings sometimes go through a process called a bake-out, where indoor air temperatures and ventilation rates are increased for a short time when the building is not occupied. The effectiveness of bake-outs are being questioned (Raloff, 1989). The effectiveness of increased ventilation rates is also being challenged. A series of European research studies found that workers in naturally ventilated buildings had fewer building related symptoms than those in mechanically ventilated buildings, and recirculating HVAC systems may promote sick building syndrome even with increased ventilation rates (Kreiss, 1993). Another study examined the effect of changing the outdoor air supply on the symptoms of sick building syndrome experienced by 1546 office workers in four buildings over three two-week periods. Changes in the outdoor air supply did not significantly affect the frequency of the symptoms or the office worker's perceptions of the office environment (Menzies, 1993). Except for the extremely limited use of activated charcoal, airborne trace contaminants are not actively removed from indoor air in residential or office buildings.

SPACECRAFT TRACE CONTAMINANT CONTROL

While venting is the primary mechanism of removing trace contaminants from commercial and residential buildings, venting is not allowed on spacecraft. Spacecraft designers are concerned that vented gases will condense on the outside surfaces of spacecraft, damage optical surfaces, and degrade with radiation exposure into caustic substances. Because of these concerns, the baseline venting allowances for the Space Station are presently limited to 100 liters per vent with the maximum concentration of most organic gases limited to 500 ppm (Martin, 1992).

The primary methods of spacecraft air quality control are; (1) source control, (2) active filtering and removal of VOCs from the cabin atmosphere, and (3) destruction of VOCs where the organics are chemically or biologically converted into carbon dioxide and water. The sophistication of air quality control systems increases as mission duration increases.

The Mercury, Gemini, Apollo Command Module, and Apollo Lunar Module all removed particles and VOCs from the cabin air with a series of filters, canisters of activated charcoal, and canisters of LiOH. Skylab also used filters, activated charcoal, and LiOH, but the Skylab was also vented between missions to help avoid long term contaminant buildup. The Russian space stations Salyut and Mir fly filters and activated charcoal canisters, and they also have ambient temperature catalytic chemical absorbents. These catalysts are expendable (Diamant, 1990).

The Shuttle Orbiter, Spacelab, and proposed Space Station trace contaminant control systems use traditional "scrubbers" (filters, LiOH, and activated charcoal canisters), but they also have systems that convert contaminants into less harmful substances. The Space Station has plans to fly a high temperature catalytic oxidizer that will mineralize a wide range of volatile organic contaminants. The Shuttle Orbiter and Spacelab fly an ambient temperature catalytic oxidizer (ATCO) which converts CO to CO_2 (Diamant, 1990).

Residential and commercial buildings with high levels of combustion products (often from cooking stoves or cigarette smoking) often have excessively high levels of CO. In many cases, increasing the ventilation rate can reduce the concentration of many of the smoke constituents, but effective removal of CO would require unrealistic ventilation rates (DHEW, 1979). Although the use of an ambient temperature catalytic oxidizer to destroy CO in a residential setting is not reported anywhere in the literature, there may be some potential uses for an ATCO to reduce the level of CO in a residential setting.

MITIGATION TECHNIQUES: SOURCE CONTROL

The most effective method of spacecraft air quality control has been a rigorous program of source control. All materials must be approved by a Payload Safety Review Board before they can be flown on the Shuttle Orbiter. Minimizing the off gassing products and flammability potential is a primary concern in the materials approval process. Materials must undergo two separate tests before acceptance for use in flight hardware. The material is first subjected to flammability and off gassing testing. After all of the materials used in the flight hardware are approved separately, the assembled piece of flight hardware is subjected to a second test. This second off gassing test of the finished flight item is performed to ensure that any VOCs are released at safe levels (Limero, 1990).

	Concentration Level (ppm)	
Compound	7-day SMAC	ACGIH TLV
Isobutyl alcohol	40	50
Ethylene glycol	50	50
Phenol	2.0	5.0
Acetaldehyde	30	100
Formaldehyde	0.1	1.0
Methyl styrene	30	50
Ethylene chloride	10	10
Trichloroethylene	0.1	50
Freon 21	5.0	10
Freon 112	100	500
Isopropyl ether	50	250
Cyclohexane	60	300
Acetone	300	750
Ammonia	25	25
Carbon monoxide	25	50
Sulfur dioxide	1.0	2.0

7-day SMAC is the maximum concentration of individual contaminants allowed in spacecraft atmospheres. Threshold Limit Value (TLV) is the recommended maximum 8-hour per day weighted average concentration of a toxic contaminant that may be present in the industrial workplace atmosphere.

Table 2. Maximum Allowable Concentrations for Spacecraft and the Work Environment (from Coleman, 1990 and ACGIH, 1993)

The acceptable levels of the individual chemical contaminants are defined as Spacecraft Maximum Allowable Concentrations (SMACs). A list of representative 7-day SMAC limits are listed in Table 2, along with a list of Threshold Limit Values (TLVs) which are the recommended maximum concentrations for workplace environments. SMAC and TLV guidelines can provide a standard for indoor air quality, assist in material selection and off gassing standards, and also drive the design of air quality control systems and building designs.

Builders and engineers concerned with air quality control for commercial and residential buildings do not focus on materials selection nearly as much as spacecraft designers. Some states have legislation limiting the amount of Urea Foam Formaldehyde Insulation (UFFI) used in mobile homes. Some Wisconsin homes with excessively high levels of formaldehyde had pressed-wood and UFFI removed after the buildings were found to have unsafe levels of formaldehyde. This source removal proved to be an effective (if expensive) solution to the indoor air problem (Dally, 1981).

Careful selection of building materials, especially insulations, adhesives, caulks, and particle boards could improve indoor air quality by limiting much of the contaminant source. Building designers should remember the increased ventilation needs, energy cost, and indoor air quality problems associated with cigarette smoking when establishing smoking areas in buildings.

MITIGATION TECHNIQUES: PHOTOCATALYTIC OXIDATION

Advanced Trace Contaminant Control Systems are needed to support missions of longer durations. VOC removal systems based on non-regenerable "scrubbers" such as activated charcoal or LiOH become excessively large as mission length increases. Advanced TCCS concepts must operate at ambient pressure and temperature, treat a wide range of organic contaminants found at low concentrations, use no expendables, and have low energy requirements. An advanced system that could capture organic contaminants and convert them to useful product gasses would reduce the need for make-up gasses. Two concepts; photocatalytic oxidation and uptake by higher plants, appear to have many of the attributes needed for an advanced TCCS. They are presently being studied for future use in spacecraft TCCS and will be described in the next two sections.

Photocatalytic oxidation is an ambient temperature process in which the surface of an illuminated semiconductor (often TiO_2) acts as a reaction catalyst by using bandgap light as a source of solid excitation. The source of light can be UV lamps of solar light. When illuminated by photons with sufficient energy, the valence band electrons in the semiconductor are photo-excited into the conduction band, creating highly reactive electron-hole pairs. If the electron-hole pair encounters a water molecule, a highly reactive OH radical is formed. If the electron-hole pair encounters an O_2 molecule, O_2^- is often formed. If volatile organics are introduced into a photocatalytic reactor in the presence of oxygen or water, they will eventually be converted to CO_2, simple acids, and water (Peral, 1992). The rates of photocatalytic reactions, effect of contaminant concentrations, effect of humidity, and photocatalytic reactor design are the subject of ongoing research.

Many researchers have reported using photocatalysis to successfully purify contaminated water (Ahmed, 1984) and the treatment of trichloroethylene and perchloroethylene in water has been the first commercially successful photocatalytic process. Solar energy has been used as a light source to keep energy costs down (Nimlos, 1992). Studies involving gas phase heterogeneous photocatalysis are far fewer, but the modest existing literature has demonstrated that near-UV illumination in concert with a TiO2 photocatalyst and molecular oxygen can carry out the complete oxidation of methane, benzene, ethane, toluene, trichloroethylene, acetaldehyde, isobutyric acid, isoprene, ammonia, methyl mercaptan, hydrogen sulfide, formaldehyde, and carbon monoxide (Peral, 1992 Raupp, 1992 Suzuki, 1993 and Nimlos 1992).

Raupp has studied the reaction kinetics of a range of halogenated and aromatic organics. He has found that the reaction kinetics are sufficiently fast so that complete hydrocarbon oxidation can be achieved with no formation of partial oxidation products. Raupp and Peral have reported reaction rate dependencies on O_2, H_2O, and contaminant concentration. Organic contaminant and O_2 exhibit Langmuir type rate dependencies, the effect of water vapor is more complex. With no water, rapid oxidation rates cannot be sustained and the catalyst eventually becomes deactivated, at high water concentrations the reaction rate decreases, and at low water concentrations reaction rates are the most favorable. Nimlos has demonstrated photocatalysis of organics in an airstream with a solar trough reactor.

Photocatalytic oxidation is being investigated as a way to treat the air in passenger areas of automobiles (Suzuki, 93). Contaminants in the air of automobile cabins come from the off-gassing of interior materials and adhesives, and from cigarette smoke, pet odors and passenger metabolic products. Acetaldehyde, toluene, isobutyric acid, isoprene, ammonia, methyl mercaptan, and hydrogen sulfide were all tested in a stirred box reactor using a TiO_2 coated honeycomb support. The rate constant of photocatalytic reaction of these contaminants was found to be pseudo first order (see figure 1). Suzuki's study is well suited for considering spacecraft trace contaminant control and indoor air quality. Contaminant concentrations used in this study are realistically low, and the oxygen concentration and humidity is nominal for indoor air. Three aspects of this study make photocatalysis an appealing technique for treating airborne trace contaminants; (1) destruction is pseudo 1st order, and contaminants found in low concentrations can be removed, (2) degraded catalysts could be refreshed by exposing the bed to UV light and clean air, (3) acetaldehyde was found to be completely oxidized to CO_2 with no intermediate reaction products. Complete oxidation is especially important to spacecraft contaminant control. Air purification using O_3 can lead to partially oxidized substances that remain as noxious contaminants.

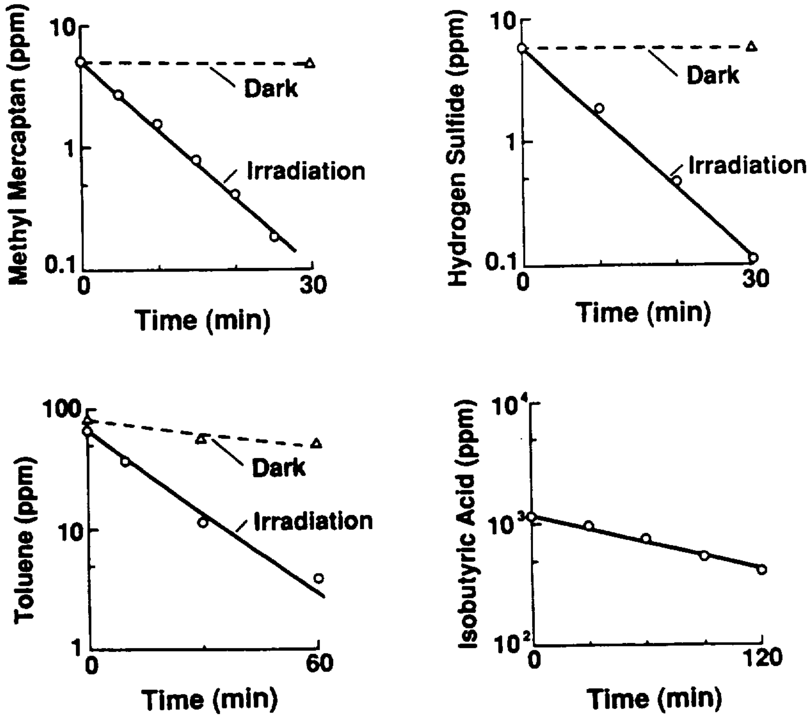

Figure 1: Reactions of contaminants in air at room temperature in the presence of TiO2 photocatalyst. The reactor uses a 500 watt UV lamp, a 20 L reaction chamber, a photocatalyst 30mm in diameter and 50 mm in length, and a 5L/min recirculating pump (from Suzuki, 1993).

Taken all together, the findings of Suzuki, Peral and Ollis, Raupp, and Nimlos indicate a favorable technical potential for photocatalyzed treatment of air in order to degrade and remove all major classes of oxidizable contaminants. The catalyst sometimes degrades and deactivates, but can be refreshed by exposing to the catalyst to light and fresh air. A wide variety of organics can be treated at low concentrations, contaminants can be completely oxidized, and the operating costs of treating large amounts of air can be greatly reduced if solar energy is used. A solar trough reactor may have great potential for commercial and residential applications.

MITIGATION TECHNIQUES: UPTAKE BY HIGHER PLANTS

Chamber studies have demonstrated that when plants were exposed to contaminant gasses (ozone by Rich 1970, sulfur dioxide by Spedding 1969), the contaminants were taken up by the plants, rapidly when the lights were on and slowly when the lights were off. Further studies have shown that the uptake of ozone and sulfur dioxide are controlled by the same resistors as the loss of water, so the cleansing of air can be realistically simulated. One simulation involving representative greenhouse conditions and 140 ppb ozone concentrations calculated that if scrubbing goes on for one hour, foliage will remove about an eighth of the ozone in the air mass above it (Waggoner 1971). Another chamber study has demonstrated that higher plants biologically uptake a wide range of organics including; ethyl alcohol, acetone, methyl alcohol, ammonia, formaldehyde, and xylene (Wolverton, 1992).

Plants remove VOCs from the surrounding air by two mechanisms; diffusion based mass transfer through the leaves, and degradation by microorganisms associated with the roots. The mechanisms of VOC removal have been confirmed with chamber studies which compared the removal rates of plants with exposed soil, plants with soil covered with a sterilized material, exposed soil with no plant, and soil covered with a sterilized material (Wolverton, 1993). The uptake by leaves is a function of the concentration of the pollutant (greater concentration drives faster uptake) and the properties of the plant. Rate of pollutant uptake is influenced by the effective plant surface area and the density of its active sites, by total diffusion resistance, and by metabolic activities (Rogers, 1977). The rate of degradation by microorganisms associated with the roots is often limited by mass transfer of VOCs into the soil.

Plants remove a wide range of VOCs from the surrounding air, but they also emit organics into the air. Plants emit a wide range of species, but isoprene and methane are the compounds most frequently reported (Sharkey, 1991). The effects of trace gas emissions by plants into indoor air must be more thoroughly understood before plants can be used in a closed spacecraft atmosphere. In a partially vented residential setting, low level emissions of trace gases from plants may be less critical.

The challenge of using plants to remove VOCs from indoor air is to make a few plants treat a large amount of air. Rogers reports that in a well mixed, well lit chamber with initial NO_2 concentrations of .5ppm, six soybean plants removed 459 μg NO_2/hr. Wolverton reports that two Boston ferns would be capable of removing formaldehyde from a 9.3 m^2 office area with a 2.4 m ceiling height. Wolverton's projection may prove to be overly optimistic, because it is based on chamber studies where the initial formaldehyde concentration is more than 10 times the TLV. In an office area where formaldehyde concentrations are lower and gas mixing less vigorous, formaldehyde uptake will likely be less efficient than chamber studies.

Common interior house plants that thrive in low-light conditions (including Boston fern, dieffenbachia, ficus, chrysanthemum and Janet Craigs) have demonstrated the ability to remove significant quantities or VOCs from sealed chambers. Some plants are more effective in removing organic chemicals than others. Studies to identify especially effective plants, along with studies to understand the removal efficiencies of VOCs in low concentrations for long durations are the subject of active research. Interior house plants such as ferns and mums may be a cost effective way of improving the indoor air quality in "tight" buildings. The only limit to the number of house plants used relates to indoor humidity. House plants transpire water, and too many plants make indoor air excessively humid.

There is another biological method for removing VOCs from air. Although Biological Air Filters (BAFs) may not be especially well suited to indoor air systems that recirculate air, they have a great potential for many industrial and environmental applications and should be briefly mentioned. Biological air filters have been used to treat VOC and air toxics emitted from industrial facilities such as foundries and print shops (Leson, 1991). Biological air filters are especially well suited to off-gas streams that contain low concentrations of volatile organics. Product gasses are vented through a biologically active solid material (often moist composted soil) and the organics are aerobically digested in the filter. These systems have low energy requirements and reduce contaminants completely to CO_2, water, and microbial biomass. More than 500 BAFs have been built in the last decade in Germany and the Netherlands, many in response to strict environmental legislation. It has been proposed to use Biological Air Filters for Air Quality Control on spacecraft (Binot, 1989). Presently the fundamental technical issue of BAFs for spacecraft and indoor air is humidity. Air coming into a biological air filter must be saturated with water or the filter will dry out and the microbes in the filter will die. Air exiting a BAF is too moist to be recirculated directly into a building or spacecraft. Until a "dry" biological air filter is demonstrated, the use of BAFs will be restricted to industrial applications where moist product gas can be vented directly.

CONCLUSIONS

There are many similarities between the indoor air quality requirements for spacecraft and "tight" commercial and residential buildings. Both indoor air quality control systems must operate at ambient pressure and temperature, treat a wide range of organic contaminants found at low concentrations, produce no toxic by-products, use no expendables, and have low energy requirements. NASA is presently using two technologies; rigorous material selection for source control, and ambient temperature catalytic oxidation, that may have application in commercial and residential buildings. NASA is also studying two advanced technologies; photocatalytic oxidation and uptake by higher plants, that may prove to be useful methods of indoor air quality control. Building designers and environmental engineers should learn more about these four systems, and consider applying them to commercial systems where they are most appropriate.

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